Simulation of Temperature Fields in Microwave Processing of SiC_f/SiC Composites

Jon Binner[1], Roger Morell[2], Matthew T. Porter[1], Petra Kumi[3], and Vadim V. Yakovlev[3]

[1]School of Metallurgy and Materials, University of Birmingham, Birmingham, U.K.
[2]National Physical Laboratory, Teddington, London, U.K.
[3]Department of Mathematical Sciences, Worcester Polytechnic Institute, Worcester, MA, USA

Keywords: ceramic matrix composites, microwave heating, multiphysics simulation.

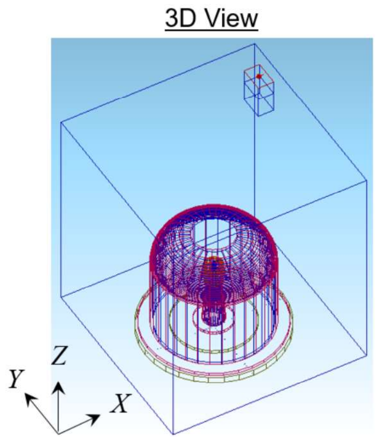
INTRODUCTION

The aerospace industry is one of the largest and arguably the most important to the composite materials sector. For many aerospace applications, the exceptional mechanical properties of composites, such as high strength, low weight and high stiffness are of utmost importance [1]. To this end, chemical vapor infiltration (CVI) is a promising advanced manufacturing technology [2]. CVI is a process in which a solid substance is deposited into a porous preform by the thermal decomposition of a reactive gaseous mixture. This process may be at least an order of magnitude quicker and more energy-efficient if carried out under the influence of a microwave (MW) or RF field [3]-[5]. However, our most recent advancement of MW-enhanced CVI has provided insight on unexplained experimental observations and a lack of reproducibility.

Here we present computational results aiming to clarify the puzzling facts, understand causes for the formation of microwave-induced temperature fields, and suggest a means for achieving superior control of the equipment. Simulations were carried out on the process involving heating of layered discs of woven SiC fibers.

METHODOLOGY

A computer model reproduces the experimental system, which consists of a large microwave cavity with waveguide excitation (SAIREM's Labotron HTE M30KB CL PRO) and a SiC fabric disc sandwiched between two alumina foam rings encapsulated in a quartz reaction chamber, as shown in Figure 1. The temperature characteristics of the electromagnetic (EM) and thermal (T) material parameters for quartz and alumina foam were obtained from the literature and measured expeirmentally for the SiC fabric; they serve as input data for the model. A finite-difference time-domain (FDTD) EM model built in the *QuickWave*™ (*QW*) [6] environment generates frequency characteristics for the reflection coefficient at five temperatures, in the range from 25 to 1,200°C, as represented by corresponding values of of the EM material paraemters. An EM-T coupled model is



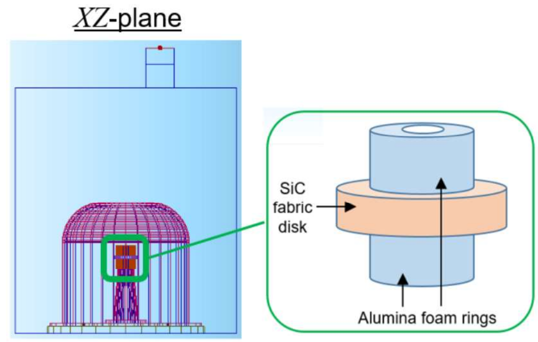


Figure 1. Three- and two-dimensional views of the model of the processed ceramic materials in the SAIREM's Labotron HTE M30KB CL PRO system.

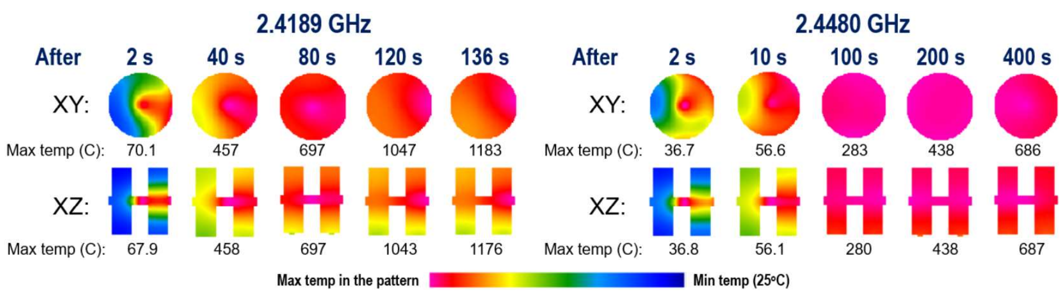


Figure 2. Evolution of the temperature field in the central horizontal plane through the SiC fabric disc (diameter 55 mm, height 8 mm) (*XY*-plane) and in the central vertical plane through the disc and the alumina foam rings (outer diameter 50 mm, inner diameter 14 mm, height 25 mm) (*XZ*-plane); fast (at 2.4189 GHz) and slow (at 2.448 GHz) heating simulated with the heating time step in the EM-T iterative procedure being 0.5 s and 1.0 s, respectively; input power 1,100 W.

implemented with the *QW Basic Heating Module* (*BHM*) [6] as an iterative procedure simulating temperature fields at ten frequencies, a mixture of resonant and non-resonant.

RESULTS

Simulations of the heating of the SiC fabric discs at the frequencies at which the reflection coefficient increases, decreases and stays nearly unchanged with increasing temperature were carried out. Accordingly, the heating at those frequencies appears to happen with very different heating rates; temperature patterns in Figure 2 illustrate examples of two typical (one fast and one slow) processes.

By both visual inspection of the pattern and using quantitative metric of uniformity of heating patterns η [7], we conclude that the slower processes provide more uniform temperature distributions within the processed composite than the fast ones; that can be contributed to high thermal conductivity of SiC fabric. The values of η varies from 0.02 (the slowest heating) to 0.1 (the fastest one).

The results obtained for the input power of 1,100 W show that at frequencies at which energy coupling is high, the maximum temperature (T_{max}) of 1,200°C can be reached in 120-220 s. When the coupling is poor, the SiC disc may not be heated up to T_{max} = 700°C even after 400 s. The slow processes provide more uniform temperature distributions than the fast ones, however; in the latter, when T_{max} ~ 1,200°C, the minimum temperature (T_{min}) may be about 900°C. Analysis of the patterns suggests that the time evolutions may be combinations of two trends: amplification of the field magnitude in the *hot spots* and spreading of the peaks of the distributions due to thermal conductivity. Our results show and explain all such experimentally observed phenomena as a change of heating rate with time, substantial variations in process characteristics due to minor geometrical changes, etc

DISCUSSION AND CONCLUSION

With an unknown frequency characteristic of the magnetron source feeding the microwave system, the developed coupled EM-T model did not intend to mimic the actual ME-CVI production of the SiC_f/SiC composites. Instead, the objective of the modeling effort was to break down the complex EM-T occurrence into multiple components in order to help analyze it, explain some experimental observations, and suggest a means of better control over the process.

For the disc of 55 mm diameter and 8 mm height, computations have revealed about 40 strong resonances in the 2.4-2.5 GHz frequency range. Simulation of heating by microwaves at different, even very close, frequencies has shown very different heating rates and temperature patterns which has explained the effect of the strong sensitivity of the performance on small changes in geometry. Variation of frequency characteristics with temperature sheds some light on the variation of the heating rate in time with the input power remaining constant. The results indicate that potential benefits to the ME-CVI process would occur with the use of a solid-state microwave source.

REFERENCES

[1] V. Giurgiutiu, Ed., *Structural Health Monitoring of Aerospace Composites*, Academic Press, 2015.

[2] O. Florez, R.K. Bordia, D. Nestler, W. Krenkel, and G. Notz, Ceramic fibers based on SiC and SiCN systems: current research, development, and commercial status, *Advanced Engng Materials*, vol. 16, no 6, pp. 621-636, 2014.

[3] D. Jaglin, J. Binner, B. Vaidhyanathan, C. Prentice, B. Shatwell, and D. Grant, Microwave heated chemical vapor infiltration: densification mechanism of SiC_f/SiC composites, *J. Am. Ceram. Soc.*, vol. 89, no 9, pp. 2710-2717, 2006.

[4] J. Binner, B. Vaidhyanathan, and D. Jaglin, Microwave heated chemical vapour infiltration of SiC powder impregnated SiC fibre preforms, *Advances in Applied Ceramics*, vol. 112, no 4, pp. 235-241, 2013.

[5] J. Binner, V. Venkatchalam, and M.T. Porter, High and ultra-high temperature ceramic matrix composites fabricated by rapid chemical vapour infiltration, *44th Intern. Conf. & Expo on Advanced Ceramics and Composites, Daytona Beach, FL, January 2020,* pp. 30-31.

[6] *QuickWave*, 1998-2019, QWED Sp. z o.o., www.qwed.com.pl.

[7] P. Kumi and V.V. Yakovlev, Computational procedure for quantitative characterization of uniformity of high frequency heating, *Proc. 53rd IMPI Microwave Power Symp., Las Vegas, NV, June 2019*, pp. 123-125.